MINERνA: a dedicated neutrino scattering experiment at NuMI

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MINERνA is a dedicated neutrino cross-section experiment planned for the near detector hall of the NuMI neutrino beam at Fermilab. I summarize the detector design and physics capabilities of the experiment.

MINERνA is a dedicated neutrino cross-section experiment planned for the NuMI beamline at Fermilab [1]. The advent of high rate neutrino beamlines designed for studies of long-baseline neutrino oscillation at the atmospheric δm^2, such NuMI, CNGS and J-PARC ν, opens up new potential for high rate neutrino cross-section measurements. Among those beamlines, NuMI provides the optimal combination of enabling factors – a well understood and tunable neutrino flux, a spacious near detector hall (Figure 1), and of course high flux. The rate of neutrino charged-current interactions in three different NuMI beam configurations in the MINERνA location is shown in Figure 2. As can be seen, a one ton target will be able to observe of order 10^5 events/eV in a run of a few years duration over a broad range of energies. Planned future upgrades to the beamline power will enhance this capability to observe neutrino interactions at high statistics in a low mass detector.

To exploit the opportunity provided by the beamline, the MINERνA collaboration is preparing to build a low-mass fully active detector interspersed with passive nuclear targets to study exclusive and inclusive neutrino interactions on a variety of nuclei at 1–20 GeV neutrino energies. Figure 3 shows the detector in a schematic view. Final states of interest will include muons, low momentum recoil protons, charged and neutral pions and electrons.

The fiducial volume in which most events are analyzed is the inner "Active Target" which is made almost entirely of scintillator strips. This low-density active target allows for separation of final state particles before they create hadronic or electromagnetic showers and enables the identification of individual particles through the properties of their tracks in the segmented scintillator. The strips are assembled into hexagonal planes with distinct orientations of strips offset by 60° which allow reconstruction of three-dimensional tracks.

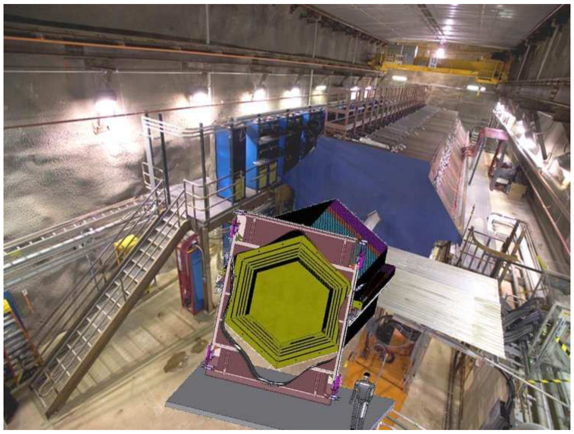

Figure 1. An isometric engineering model of the MINERνA detector as it is to be installed in the NuMI hall.

However, the active target does not fully contain forward and sideways going particles due to its low density and low Z, so the MINERνA design surrounds it with sampling detectors. In these sampling detectors, scintillator strips are intermixed with absorbers. For example, the side and downstream (DS) electromagnetic calorimeters (ECALs) have 2 mm thick lead absorbers in front of each plane of scintillator. Surrounding

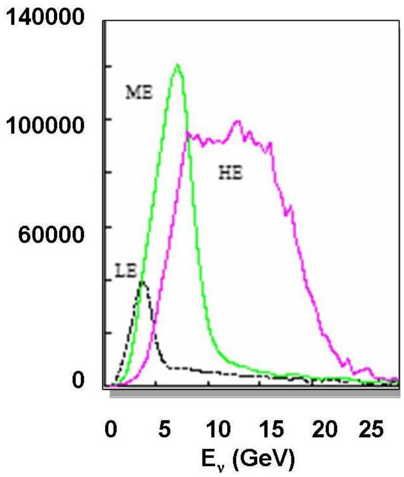

Figure 2. The rate of charged-current interactions per ton of material per GeV in 2.5×10^{20} protons on target, a nominal year of NuMI running.

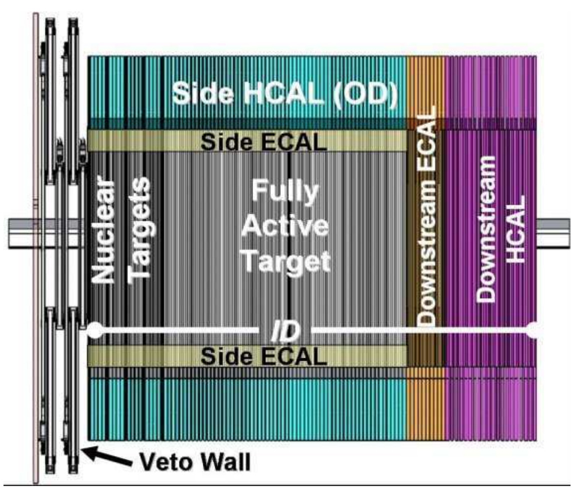

Figure 3. A schematic side view of the MINERνA detector with sub-detectors labeled. Neutrinos enter from the left in this figure and the MINOS near detector, which serves as the MINERνA muon momentum analyzer, is to the right in this figure.

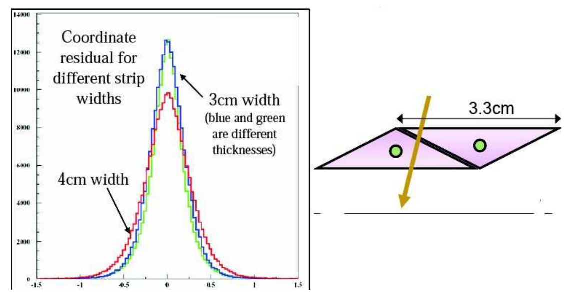

Figure 4. Coordinate resolution from charge sharing in adjacent strips for tracks of muons from quasi-elastic scattering.

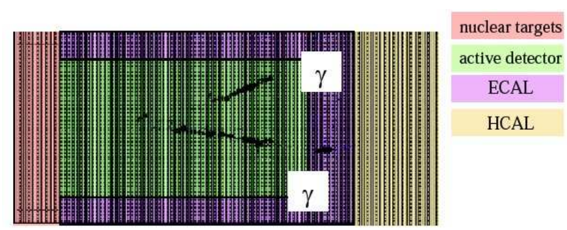

Figure 5. A typical event containing a π^0 in the final state, $\nu_\mu \to \mu^- p \pi^0$. The photons from the $\pi^0 \to \gamma\gamma$ decay are observed as broad tracks in the detector, well separated from the point of interaction in the scintillator.

the ECALs are the hadronic calorimeter (HCAL) and outer detector (OD) which intersperse scintillator with steel absorber. Upstream of the detector is a veto of steel and scintillator panels to shield MINERνA from or identify the presence of incoming particles produced in the material upstream of the detector. Downstream of MINERνA is the existing MINOS near detector, which will measure the energy of muons which do not exit through the OD. Finally the nuclear target region has planes active scintillator interspersed with passive absorbers in order to study interactions on nuclei other than carbon.

With the low mass design allowed by the high intensity NuMI beam, MINERνA's response to single particles for exclusive final state identification is more similar to a bubble chamber

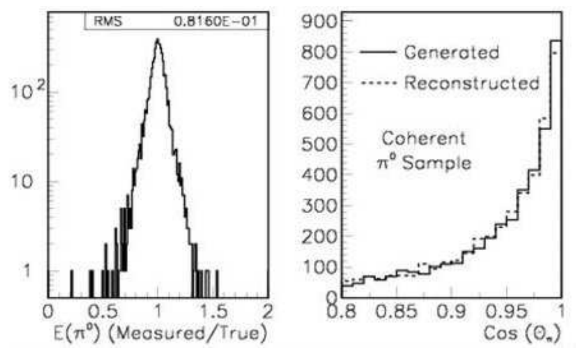

Figure 6. Energy and angular resolution for reconstructed π^0s from produced in coherent scattering from a carbon nucleus. As can be seen in the figure at right, the generated and reconstructed angular distribution in forward-peaked coherent production are nearly identical.

than to previous high-rate neutrino detectors. MINERνA's performance has been studied extensively in a hit-level simulation, including the photo-statistical effects of light collection, a realistic Kalman filter reconstruction package for track and vertex fitting, and particle identification. The fully-active region of the detector has excellent performance for tracking and identification of single particles in the final state, including low-energy recoil protons from low-Q^2 $\nu n \rightarrow \mu^- p$ reactions. Charge sharing between adjacent triangular strips allows excellent spatial resolution. For μ^- from quasi-elastic interactions, the expected hit resolution per detector plane is $\sim$ 3 mm as shown in Figure 4. Fitted tracks from such muons have typical impact parameter and angular resolution of $\sim$ 2 mm and $<$ 9 mrad. Using the (typically short) reconstructed proton track and the muon track from quasi-elastic events, RMS vertex uncertainties of 9 mm and 12 mm are measured in the coordinates transverse and parallel to the beam direction, respectively. Measured energy loss (dE/dx) is an excellent tool for particle identification in MINERνA. For tracks which stop in the inner detector, the charge deposited near the end of the track (corrected for sample length) can be compared with expected curves for $\pi^\pm$, $K^\pm$ and protons.

With the surrounding ECALs for energy containment, MINERνA's π^0 reconstruction capabilities are excellent. This is essential, since final states with π^0's are a major source of background for ν_e appearance oscillation experiments. As shown in Figures 5 and 6, MINERνA's low density and high granularity make it an excellent photon tracker, able to accurately reconstruct the vertex and kinematics even for a coherently-produced π^0 with no accompanying charged tracks. Kinematic reconstruction allows coherent and resonant π^0 production to be distinguished.

MINERνA Detector Technology

The active element of the inner scintillator detector consists of extruded polystyrene scintillator strips of triangular cross-section with a 17 mm height and a 33 mm base. The polystyrene is mixed with 1% PPO and 0.01% POPOP in a continuous in-line extrusion process, and an accompanying co-extruder places a $\sim$ 0.2 mm reflective layer of TiO_2 loaded polystyrene on the outside of the strips. In the center of the triangle, the extruder also leaves a $\sim$ 2 mm diameter hole in which is placed a 1.2 mm Kuraray multi-clad S-35 fiber doped at 175 ppm of Y-11 waveshifter. In the MINERνA detector, the wavelength shifting (WLS) fibers are approximately 3 m long, and are read out on one end while the other end is mirrored by vacuum deposition of Al to obtain 80% reflectivity. The fiber is potted into the hole with an optical epoxy which increases the light yield by a factor of 1.5. The WLS fibers are bundled into groups of eight and terminated in a DDK MCP-8A fiber connector. Clear fiber cables with an average length of 1.5 m take the light from the WLS fibers to Hamamatsu R7600U-00-64 MAPMTs with photocathodes selected for high quantum efficiency for green light. The MAPMTs are enclosed in a dark box mounted onto the structure of the outer connector. The clear fiber cables are connected *via* an identical DDK connector to a clear fiber bundle which terminates at the the MAPMT in

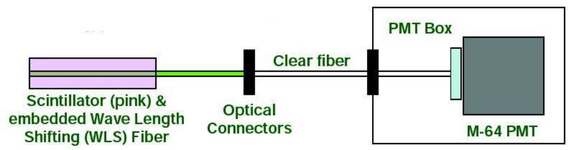

Figure 7. The light collection chain in the scintillator strips of the MINERνA detector.

a fiber placement "cookie" that is aligned to the pixel pattern of the MAPMTs. The light collection chain is shown schematically in Figure 7.

For front-end digitization of the MAPMT signals, a design based on the D0 TRiP ASIC [2] has been developed and tested. MAPMTs are connected by short ribbon cables to the front-end boards on each PMT dark box to minimize input capacitance to the TRiP amplifiers. The front-end boards include a Cockroft-Walton high-voltage supply for the tube. Both the pulse-height and time (used for identification of strange particles and muon decays) of each hit are digitized. Digitized signals are collected by custom VME readout controllers through LVDS chains of twelve front-end boards and transferred to the data acquisition computer over a PCI-VME bridge. Slow control messages are also exchanged with the front-end boards over the LVDS readout chains.

This entire chain of light collection, electronics and readout has been tested in a "vertical slice test" (VST) array consisting of three layers of of scintillator strips in small planes. Based on the results from this test, the light yield is projected to be 4.6–5.4 photoelectrons/MeV of deposited energy in the strip, depending on where in the along the strip the particle passes.

Prototypes of most other detector components have been produced and tested individually. The detector will be assembled in planar modules. The OD portion of each module consists of a hexagonal-shaped steel frame with slots of scintillator, and it provides the structural support for the detector. Inside each frame is one or two planes of scintillator. The side ECAL is constructed simply by placing lead absorber around the outside of each scintillator plane, and ECAL and HCAL modules have scintillator planes interspersed with thin lead or thick steel absorbers covering the full face of the scintillator. The inner detector scintillator is glued into planes and wrapped with opaque material. The glued WLS fibers are supported by semi-flexible routing guides which bring the fiber through the gaps of the OD frame. Clear fiber cables are constructed with fiber which is undoped but otherwise identical to the WLS fiber. These fibers are encased in PVC tubes that are potted into the connector with a dark pigmented polyurethane.

Physics Goals of MINERνA

The physics of neutrino cross-sections is an exciting subject which explores physics in the axial current similar to that being probed at high precision in the vector current at high intensity electron scattering machines. The physics goals of MINERνA include measurements of the A-dependence of quasi-elastic ($\nu n \to \mu^- p$) and deep inelastic scattering, measurement of the axial form factor of the nucleon at high Q^2, tests of quark-hadron duality in the axial current, measurements of coherent single-pion production in the Coulomb field of a target nucleus, neutrino production of strange particles, and measurement of a wide variety of exclusive low-multiplicity neutrino reactions across a broad range of energies. For reasons of space, I highlight only two of these measurements here.

The best measurements today of the charged-current quasi-elastic cross-section are have statistical and systematic errors each in the range of 10–20%. A full simulated analysis of the quasi-elastic channel in MINERνA has been carried out [3]. The efficiency and purity of the final sample are Q^2 dependent with an average efficiency of 74% and purity of 77%. The expected results are shown in Figure 8. MINERνA will measure the cross-section on carbon up to E_ν of 20 GeV with statistical errors ranging from $\leq 1\%$ at low E_ν up to 7%.. The expected beam systematic uncertainty is 4–6% because of precision measurements of hadron production (the largest uncertainty in predicting neutrino flux) by the MIPP experi-

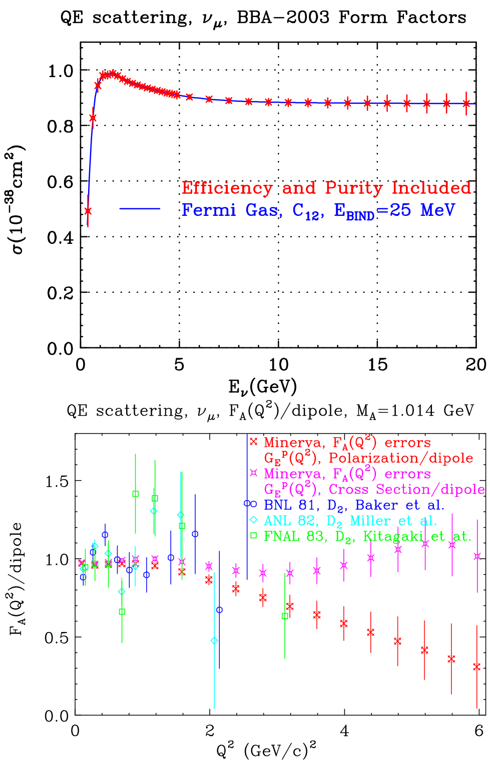

Figure 8. At top is the simulated cross-section measurement for MINERνA in a 4-year run (statistical errors only). At bottom are the projected axial form-factor results for MINERνA for two different assumptions: F_A/dipole=G_E^p/dipole from cross-section and F_A/dipole=G_E^p/dipole from polarization. Also shown are measurements from the deuterium bubble chamber experiments Baker *et al.* [6], Kitagaki *et al.* [7] and Miller *et al.* [8].

ment [4]. In addition, the MINERνA nuclear targets will allow comparison of quasi-elastic scattering cross-sections from carbon, iron and lead targets. Turning to high Q^2, the large Q^2 behavior of G_E^p has turned out to be an evolving and surprising story in recent years [5]. Figure 8 shows the extraction of the axial-vector form factor from the quasi-elastic $d\sigma/dQ^2$ measured in MINERνA over a 4-year run. Since MINERνA can measure the axial nucleon form-factor at high Q^2 with precision comparable to vector form-factor measurements at JLab, combining them with present and

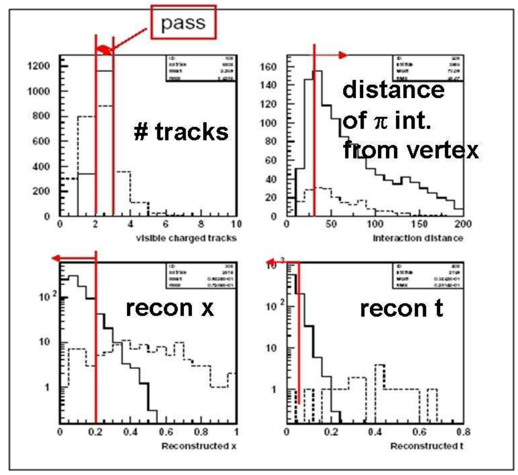

Figure 9. An illustration of selection variables used to isolated charged-current coherent pion production from nuclei in MINERνA.

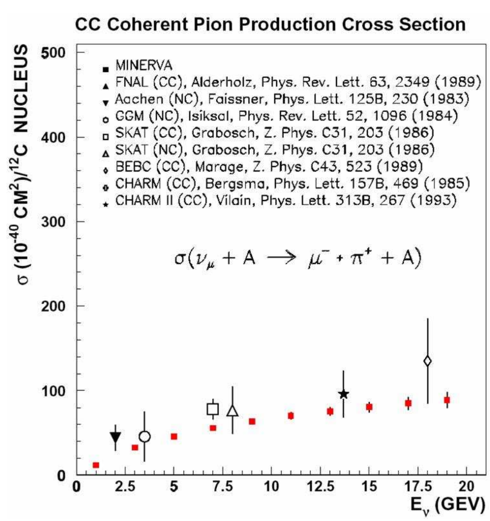

Figure 10. The expected uncertainties on cross-sections from charged-current coherent scattering as a function of energy.

future Jefferson Lab data will permit precision extraction of all form factors needed to improve and test models of the nucleon.

Both charged and neutral-current coherent pion production in the Coulomb field of the nucleus result in a single forward-going pion with little energy transfer to the target nucleus. The neutral current reaction, with a forward-going π^0, can mimic an electron in coarse or sampling detectors, and can therefore provide background to ν_e appearance in oscillation experiments. Existing cross-section measurements for this reaction are only accurate to 35%, at best, and only available for a limited number of target nuclei at few to ten GeV in energy [9]. In addition, recent data from K2K SciBar detector suggests some surprising behavior of the cross-section at low energy [10]. MINERνA, with its high statistics and variety of nuclear targets, will greatly improve our experimental understanding of coherent processes. A complete simulated analysis of the CC coherent production channel has been carried out [11]. The kinematic cuts employed reduce the background by three orders of magnitude while reducing the signal by only a factor of three. MINERνA will be able to precisely measure the cross-section as a function of energy, as shown in Figure 10, and will also compare coherent scattering cross-sections on various nuclei for the first time.

These measurements and others planned for MINERνA are also important for future neutrino oscillation experiments planned with beams of energies 1–few GeV. In this region at the transition between elastic and inelastic scattering, neutrino cross-sections are difficult to predict theoretically and are poorly measured [12]. Results from the MINERνA experiment will significantly reduce errors from unknown neutrino cross-sections in the MINOS, T2K and NOνA experiments.

Conclusions

MINERνA is currently poised to begin construction. The first active target module, consisting of an outer detector frame filed with two planes of scintillator strips will be produced by the end of 2006, and we expect to produce a group of between 10 and 20 prototype modules for tracking and assembly tests is 2007. Construction of the full set of over 100 modules will begin in late 2007, and we plan to have the full detector installed and operating in the NuMI beam in 2009. We look forward to presenting our results in future NuINT meetings.

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